

## A COST-BENEFIT ANALYSIS OF USING ROOIKRANS AS BIOMASS FEEDSTOCK FOR ELECTRICITY GENERATION: A CASE STUDY OF THE DE HOOP NATURE RESERVE, SOUTH AFRICA

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### Abstract

Invasive alien plants (IAPs) like Rooikrans (*Acacia Cyclops*) have several undesirable effects on both the natural environment and the social, economic and cultural wellness of society in the De Hoop nature reserve of the Western Cape Province. A few of these negative effects are: the change in coastal sediment dynamics, the change in seed dispersal dynamics, and the fact that it is overtaking native plants. However, Rooikrans can also potentially be used as biomass feedstock for electricity generation. Following a system dynamics modelling approach, the feasibility of using woody biomass from Rooikrans was investigated. The RE-model used data obtained from the Department of Environmental Affairs' (DEA) Natural Resource Management (NRM) division, consulted with experts and conducted literature reviews with respect to the subject matter. Three scenarios were tested and the RE-model results showed that all scenarios have a positive cumulative Net Present Values (NPVs), with the exception of the baseline case scenario. This study shows that the production of electricity using Rooikrans woody biomass is a viable and feasible option in comparison with electricity production by diesel generators.

**Key words:** invasive alien plants, Rooikrans (*Acacia Cyclops*), cost-benefit analysis, system dynamics modelling, RE-model, woody biomass, electricity, diesel generators, System Johansen Gasifier

JEL: Q24, 25, 42

## 1 Introduction

### 1.1 Background to the study

The De Hoop nature reserve is currently being invaded by invasive alien plants (IAPs), which are known to pose a threat to natural capital stocks. Natural capital plays a major role in the livelihoods and the economic wellbeing of society as a whole (Blignaut & Moolman, 2006; Meyer, Breitenbach, Fényes & Jooste, 2007; Rosegrant, Ringler, Benson, Diao, Resnick, Thurlow, Torero & Orden, 2006). The other forms of capital (i.e. manufactured, financial, human and social) are also dependent on natural capital and, hence, are interlinked. Additionally, the constitution of the Republic of South Africa, 1996 (Act 108 of 1996) [Section 24] states the following:

*“Everyone has the right: (a) to an environment that is not harmful to their health or well-being; and (b) to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that- (i) prevent pollution and ecological degradation; (ii) promote conservation; and (iii) secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development” (RSA, 1996).*

If left uncontrolled, Rooikrans (as well as other IAPs) would alter the biodiversity of natural ecosystems owing to the various disruptions that it causes in the De Hoop nature reserve and

wherever else it occurs. Rooikrans affects the fynbos, forest and savanna biomes of South Africa (Van Wilgen, Richardson, Le Maitre, Marais & Magadlela, 2001). The undesirable impacts caused by Rooikrans vary, and include the following:

- changes in coastal sediment dynamics (Avis, 1989);
- uses a lot of water (De Beer, 1986; Van Wilgen et al., 2001);
- changes in seed dispersal dynamics (Fraser, 1990; Knight & MacDonald, 1991);
- outcompetes native plants (Higgins, Richardson, Cowling & Trinder-Smith, 1999; Cronk & Fuller, 1995; De Beer, 1986; Working for Water, 2003); and
- increases in litter fall (Milton, 1981; Weber, 2003).

These negative effects put pressure on the economic, social and cultural wellbeing of the De Hoop nature reserve. However, information relating to the detailed economic costs and benefits of clearing Rooikrans is poorly understood. Despite its negative effects, Rooikrans does have certain benefits, such as:

- erosion control and dune stabilisation (National Academy of Sciences, 1980);
- it provides a nesting habitat for rare African penguins (Crawford, n.d. cited in Van Wilgen et al., 2001);
- its use as an ornamental plant (Siverio & Montesdeoca, 1990);
- it causes an increase in biomass (Milton, 1981);
- used to make firewood and charcoal (NAS, 1980; Duke, 1983; Yantasath, Anusontpornperm, Utistham, Soontornrangson & Watanatham, 1993; Azorin, 1995);
- use as fodder for livestock (NAS, 1980);
- a source of medicinal and pharmaceutical properties and tannins (Duke, 1983); and
- potentially used as a feedstock for electricity generation (Mugido et al., 2013).

Currently in the De Hoop nature reserve and its surrounding areas, Rooikrans is being controlled by means of a combination of mechanical and chemical control methods (Impson, 2005; Hall & Boucher, 1977; Dennill, Donnelly, Stewart & Impson, 1999; Pitseng, 2015, pers comm; Van Staden, 2015, pers comm). This is done by cutting the tree trunks at the basal level close to the ground (Weber, 2003) and then applying an effective herbicide to the cut stem to prevent coppice from sprouting (i.e. new shoots) (Impson, 2005; Pitseng, 2015, pers comm; Van Staden, 2015, pers comm). Controlled burning is also used to complement management options in order to reduce the soil seed bank of Rooikrans and to kill the felled stems. Working for Water (2003) states that young Rooikrans plants can be pulled up by hand and medium-sized plants can actually be ring barked to control their spread. The biological control of Rooikrans using seed feeding weevils (*Melantarius* species) is also being investigated (Dennill, Donnelly, Stewart & Impson, 1999; Impson, 2005; Working for Water, 2003). Both the adults and larvae of the weevils have been shown to destroy as much as 95 per cent of the Rooikrans seeds at the experimentation sites in the fynbos biome of the Western Cape Province (Impson, Moran, Hoffmann, Donnelly & Stewart, 2000).

## 1.2 Objective of the study

Many studies have demonstrated empirically that IAPs can be managed and that their effects may be circumvented through prevention, eradication via clearing operations, or reduced through integrated control mechanisms (i.e. mechanical, biological and chemical ways), while also attempting to make a cost-benefit analysis (Van Wilgen, Cowling & Burgers, 1996; Van Wilgen, Little, Chapman, Gorgens, Willems & Marais, 1997; Higgins, Azorin, Cowling & Morris, 1997; Heydenrych, 1999; Hosking & Du Preez, 1999; Turpie & Heydenrych, 2000; Le Maitre, Van Wilgen, Gelderblom, Bailey, Chapman & Nel, 2002; Van Wilgen, Van Der Heyden, Zimmerman, Magadlela, & Willems, 2000; Van Wilgen et al., 2004; De Wit, Crookes & Van Wilgen, 2001; McConachie, De Wit, Hill & Byrne, 2003; De Lange & Van Wilgen, 2010; Mugido et al., 2013). However, this study is the first system dynamics attempt to investigate the use of Rooikrans as biomass feedstock for electricity generation. The De Hoop area has encountered electricity supply problems due to ESKOM's load-

shedding schedules. Using Rooikrans biomass as a feedstock for electricity generation and power generation via diesel generators could potentially serve as alternative options to augment ESKOM's power supply grid in order to sustain electricity provisioning on the grid. The purpose of this study is therefore to assess the economic feasibility of using woody biomass from Rooikrans for electricity generation by means of biomass gasification technology using the System Johansen gasifier. This would be rather than creating electricity generation by using diesel generators. It is important to note that this study does not seek to replace grid-based electricity but rather shows the potential economic feasibility of alternative ways in which grid-based electricity could be augmented. Thus, for the purpose of this study, the generation of electricity via biomass gasification using Rooikrans biomass and electricity generation using diesel generators were identified as some of the possible ways in which electrical energy could be generated. As a result it is imperative to compare these two alternative options of electricity generations in order to identify the best and most economically feasible option of the two.

## 2 Study site

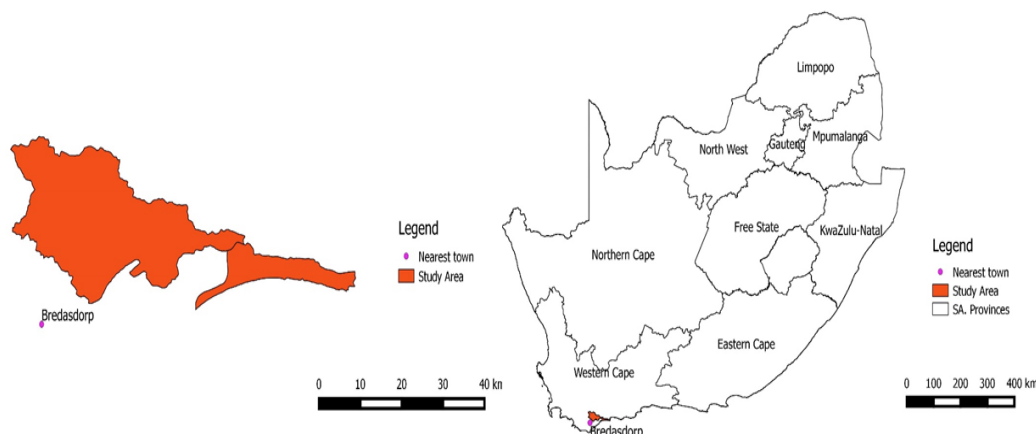
### 2.1 Site description

This study was conducted at the quaternary catchment (G50<sub>J&K</sub>) of the De Hoop nature reserve, Western Cape, South Africa (see Figure 1). The De Hoop nature reserve is a coastal reserve situated in the Overberg region approximately 50 km from Cape Agulhas, the southern tip of Africa. The climate for the De Hoop nature reserve is Mediterranean, characterised by winter rainfall with a mean annual rainfall of 500-2000 mm (South African Weather Services, 2015). The vegetation types resemble those found in the fynbos biome (Mucina & Rutherford, 2006). In terms of its geological characteristics, the coastline is generally concave and the coastal plains are upward sloping, developing into the limestone hills on the western side, with the Potberg Mountain range on the north-east side. De Hoop is characterised mainly by coastal limestone and sand, sandstone and quartzites of the Table Mountain Group, with the rolling plains of Bokkeveld shales lying further inland in the nature reserve. The diversity of plant species in the nature reserve is ascribed to the heterogeneous geological patterns. The municipal areas covering the De Hoop area have a population size of 9 225 people, with a population density of nine people per km<sup>2</sup>, an average population growth rate of 1.96 per cent and a total workforce of 6 213 people (StatsSA, 2011). The settlement type is two-pronged, with 18.40 per cent farm settlements and 81.60 per cent urban settlements. In terms of human capital development, 3.60 per cent of the population has had no schooling, 95 per cent have had some primary school education or have completed their primary education, and 1.40 per cent have reached a higher education level (StatsSA, 2011). According to Kotzé, Beukes, Van Den Berg and Newby, (2010), the major of IAPS in the studied De Hoop nature reserve catchments are Rooikrans (*Acacia cyclops*), *Pinus* species, *Acacia Saligna* and *Eucalyptus* species, with Rooikrans being the major IAP under control in the De Hoop nature reserve.

### 2.2 Ecology and biology of the Rooikrans invasive tree

Rooikrans is thought to have been introduced into South Africa in the 1830s (Cronk & Fuller, 1995; Henderson, 2001; ILDIS, 2002). It is native to the Oceania sub-continent, mainly in South and Western Australia (Jaensch, Vervest, & Hewish, 1988; ILDIS, 2002) and is also reported to be invasive in the USA. It is an alien invader in three European countries (i.e. Cyprus, Malta and Portugal) (ILDIS, 2002), two Asian countries (Pakistan and Thailand) and various African countries. Rooikrans is thought to have been introduced into Baron von Ludwig's private garden and the Cape Flats in the 1830s as an ornamental plant (Cronk & Fuller, 1995). According to Weber (2003), in its native country it grows in open scrub and seldom forms any dense canopy stands. However, Rooikrans has become a successful coloniser in South Africa, affecting three biomes (i.e. Fynbos, Forest and Savanna) (Van Wilgen et al., 2001), and is classified as a weed (Moll & Trinder-Smith, 1992; Henderson, 1998; Higgins et al., 1999).

**Figure 1**  
Location maps of the De Hoop nature reserve



Source: Department of Environmental Affairs (2015)

Rooikrans is a dense, bushy shrub that does not shed leaves and is predominantly multi-stemmed (see Figure 2). It has the potential to grow into a small tree, reaching an average height of 3–8m, complemented by a stem-width of 20 cm in diameter and a rounded crown (NAS, 1980; Little, 1983; De Beer, 1986). Rooikrans reproduces from seed (NAS, 1980) and does not usually produce shoots or coppice after the stem has been cut. The germination of the Rooikrans seed is enhanced by fire outbreaks. This IAP grows well in arid and semi-arid, subtropical areas with an average mean annual temperature of 14–19°C and an annual rainfall of 200–1 400 mm; it is also highly resilient in long, dry seasons and drought conditions. Rooikrans is slightly resistant to frost (Little, 1983; NAS, 1980; Yantasath et al., 1993) and is highly sensitive to waterlogging. In its native environment, Rooikrans thrives on calcareous sand or limestone and grows well in coarse-textured, sandy soil. Furthermore, it is able to sustain populations on both drier land like sand dune peaks (NAS, 1980) and soils characterised by extreme pH, as well as those with poor drainage, as long as they are not waterlogged. The geological characteristics of the De Hoop nature reserve are consistent with the soil characteristics that favour the growth of Rooikrans, and for this reason it is a major IAP in the catchment sites considered in this study.

**Figure 2**  
Photograph of the Rooikrans (*Acacia Cyclops*) tree



Source: ISPOTNATURE (2013)

### 2.3 Rationale for clearing IAPs in the De Hoop nature reserve

IAPs are a major disturbing factor affecting the De Hoop nature reserve, with Rooikrans being the main species. Controlling these plants is expensive, requiring funding from both the government and the private sector. Transforming the biomass of IAPs into value-added products (VAPs) could potentially help co-finance the clearing operations in De Hoop, as the revenue generated is re-invested into IAP clearing operations.

This study evaluates the economic costs and benefits of using Rooikrans woody biomass from the De Hoop nature reserve for electricity generation by means of biomass gasification technology, using the System Johansen gasifier (compared with electricity generation by diesel generators). Further, it explores the potential economic feasibility of this process and its implications for policy by providing a framework which policy-makers could use to promulgate and craft effective and feasible policies. These could help both private and public stakeholders meet the statute contained in the Constitution of the Republic of South Africa as well as to mitigate the negative effects posed by Rooikrans (and other IAPs). This study also seeks to show empirically that the costs of using woody biomass from Rooikrans for electricity generation (via the System Johansen Gasifier) is price-competitive when in comparison with electricity generation using diesel generators.

## 3 Materials and methods

### 3.1 Data

Data was obtained from the Department of Environmental Affairs' Natural Resource Management (DEA:NRM) database (2015), Cape Nature, personal site visits, focus group discussions, formal and informal telephonic interviews, consultation with experts, Statistics South Africa, the catchment management plan for the De Hoop nature reserve, and extensive literature reviews (both local and international). GIS shape files from the Department of Water and Sanitation (2015) were also used. These were processed using QGIS software to demarcate the quaternary catchment areas and the land-use cover of the respective areas under study.

#### 3.1.1 Clearing costs of major IAPs

The annual clearing costs of major IAPs, which consist of the initial and follow-up clearing costs, incurred by the DEA's Working for Water programme were extracted from the 2015 DEA:NRM database and are shown in Table 1. In the base year (2008), the clearing costs amounted to approximately ZAR828 291 and decreased by approximately 31.49 per cent in 2009. From 2010 to 2013, the clearing costs increased gradually from approximately ZAR857 430 to ZAR1 053 704, with a much lower figure (approximately ZAR609 046) incurred in 2014.

**Table 1**  
Annual clearing costs of major IAPs in the  
De Hoop nature reserve

Year of clearing	Value	Unit
2008	828 291.51	ZAR
2009	567 461.26	ZAR
2010	857 429.80	ZAR
2011	969 070.71	ZAR
2012	1 053 703.96	ZAR
2013	609 046.41	ZAR
2014	171 010.00	ZAR

Source: Adapted from DEA (2015)



### 3.1.2 Biomass from major IAPs in the De Hoop nature reserve

The potential biomass that can be produced per hectare of the condensed invaded areas in the De Hoop catchment areas under study is shown in Table 2. The baseline values for the RE-model are adapted from a report compiled for the biomass electricity production in the Nelson Mandela Metropolitan Bay (Mugido et al., 2013). The biomass data is essential to this study, as it would enable the calculation for the amount of electricity that could be produced from Rooikrans woody biomass using the System Johansen gasifier. This would help determine how much electricity could actually be produced over the period 2016–2030. For the purposes of this study, only Rooikrans is of interest for electricity generation, so the biomass from other IAPs shown in Table 2 is not considered in either the cost-benefit analysis or the power generation model. Further, Rooikrans was chosen as the IAP species of interest because it is the most dominant IAP in the De Hoop area. Moreover, most of the clearing efforts currently being undertaken in De Hoop are for the most part dedicated to Rooikrans. Additionally, amongst all the IAP species invading the De Hoop area, Rooikrans is the most suitable alien plant species when it comes to bio-energy. Other uses of IAPs include the production of timber, for example, for which pines and eucalyptus are more suitable. Bio-energy is at the bottom of the IAP value hierarchy, so it would not be economically feasible to use high-value species for low-value uses. Since the debate on how much of the higher-value IAP species should be used for higher-value uses has not been resolved, it would not be advisable to allocate high-value IAP species biomass to bio-energy when it could potentially be used to make other high-value VAPs. This would in turn inflate the electricity generation potential unrealistically. Accordingly, Rooikrans was selected for this study.

**Table 2**  
Biomass produced by the major IAPs in the De Hoop nature reserve

IAP	Value	Unit
<i>Acacia Cyclops</i>	45.00*	ton/ha
<i>Pinus spp.</i>	45.00*	ton/ha
<i>Acacia Saligna</i>	23.20	ton/ha
<i>Eucalyptus spp.</i>	45.00*	ton/ha

Source: Adapted from Mugido et al. (2013)

\*The default range for the biomass of these species is 40–45ton/ha. 45 ton/ha was used for this study

### 3.1.3 Rooikrans biomass power generation costs

The costs incurred in the production of electricity from the Rooikrans woody biomass consist of the capital cost of the System Johansen gasifier units installed and the respective variable costs associated with the bio-electricity plant. There are four units (with a capacity of 0.8 MW) in the RE-model, each at a cost of ZAR33 765 700, thus the total capital cost of ZAR135 062 800 (Stafford, Blignaut, Forsyth & Le Maitre, 2016). These units are equivalent to six diesel generators. The variable costs incurred by each System Johansen gasifier unit per year amounts to ZAR5 866 330, thus the gross total of ZAR23 465 320 (Stafford et al., 2016). The power generation costs are important to the RE-model in determining the net value of the electricity sales for the purposes of this study.

### 3.1.4 Carbon sequestration losses

The value of carbon sequestered by the major IAPs in the De Hoop Nature Reserve is shown in Table 3. Although major IAPs have negative effects on the De Hoop catchment areas under study, these can also be beneficial, including carbon sequestration. Plants use carbon from the atmosphere through the process of photosynthesis, thereby acting as a carbon sink. As a result of clearing the IAPs, the carbon sequestration potential by these plants is lost. The value of the carbon sequestration potential losses is ZAR8 910 per hectare for each plant species (i.e.  $\text{ZAR}120 \times 74.25$ ), with the exception of *Acacia Saligna*, which amounts to ZAR4 593.60 per

hectare (i.e. ZAR120×38.28). The total carbon sequestration potential loss as a result of clearing the IAPs amounts to approximately ZAR31 323.60 per hectare.

**Table 3**  
Carbon sequestration by the IAPs in the De Hoop nature reserve

IAP	Sequestered carbon	Unit	Carbon loss (ZAR)
<i>Acacia Cyclops</i> (Rooikrans)	74.25*	tCha	8 910
<i>Pinus</i> spp.	74.25*	tC/ha	8 910
<i>Acacia Saligna</i>	38.28*	tC/ha	4 593.60
<i>Eucalyptus</i> spp.	74.25*	tC/ha	8 910

Source: Adapted from Mugido et al. (2013) and Thomas and Martin (2012)

\*Carbon sequestration = (Biomass×45%)×3.6667

N.B. The carbon portion is equivalent to 45 per cent of the wet biomass weight (the approximate mean of the temperate climate). The ratio for CO<sub>2</sub> to Carbon is 3.6667 (Thomas & Martin, 2012). 55 per cent moisture content is removed to be left with the 45 per cent oven dry mass.

### 3.1.5 Total power generation potential from Rooikrans biomass

The total power generation potential from Rooikrans in the RE-model is 3 045.62 kW. This is influenced by the amount of biomass converted into electricity (i.e. 14 ton/kW) and the total biomass harvested (i.e. 42 638.7 tonnes). The System Johansen gasifier units operate for 8 760 hours per year, with a capacity use of 80 per cent. This results in the total amount of electricity of 21 343 704 kWh per year. Hence, the total value of electricity produced is ZAR34 150 000, at the cost of ZAR1.60 per kWh. The net value of the electricity sales is -ZAR116,7 million in the year 2016 owing to the capital cost incurred (i.e. total value of electricity sales – the total capital costs and total variable costs). As from 2017, however, this value will become positive, with a value of ZAR11,8 million.

### 3.1.6 Carbon emissions avoided owing to the use of Rooikrans for electricity

The generation of electricity using diesel generators is associated with high greenhouse gas emissions. Thus, generating electricity with biomass from Rooikrans using the System Johansen gasifier units is an alternative low carbon footprint. Given the total electricity generation of 21 343 704 kWh per year from Rooikrans biomass, 12 806.2 tonnes of carbon per year could be avoided if the System Johansen gasifier units were used instead of the diesel generators.

## 3.2 Method

The Rooikrans electricity model (RE-model), a system dynamics model, was developed to analyse the potential of using Rooikrans woody biomass for electricity generation in the De Hoop nature reserve. IAPs (especially Rooikrans) are responsible for major disturbances affecting the De Hoop nature reserve. However, the biomass from these IAPs could potentially be used for producing renewable energy through biomass gasification technology to produce electricity with a low carbon footprint.

The System Dynamics modelling approach enables researchers to model changes in complex systems over time while capturing realistic dynamic behaviour between variables. It includes feedback loops, lag times and non-linearities (Crookes, 2012). Smith and Van Ackere (2002) point out that system dynamics modelling does not contradict the traditional economics methods of modelling dynamic phenomena. However, system dynamics modelling enables researchers to model disequilibrium circumstances while providing a realistic, real-time portrayal of the processes involved in decision-making (Stermann, 1987). System dynamics modelling is a powerful tool when the problem under analysis is too complex to understand by using our mental models. It allows for qualitative analysis of the problem under consideration, using causal loop diagrams which show the causal effect relationships between the various interlinked components of the complex system and their feedback actions. Further this technique enables one to undertake a quantitative analysis by means of a simulation run. The problem of IAPs invading the De Hoop

nature reserve is caused by various factors and also has many effects on the environment and on society as a whole. A system dynamics modelling approach is therefore important in understanding the dynamics associated with invasion by IAPs into the De Hoop and its respective environmental, social and financial implications. It is important to note that, when running the simulation, it is important not to include too many variables as this would give rise to poor and often incorrect results.

Brown and Daigneault (2014) state that, although multi-decision criterion analysis has recently been advocated for studies investigating the control of IAPs, few studies have employed this methodology. The cost-benefit analysis approach is more common owing to its tractability, methodological transparency and wide adoption among governments and environmental policy-makers, as noted by Pearce, Atkinson & Mourato, (2006) and Brown and Daigneault (2014).

### 3.3 Model boundary chart

The model boundary chart for the system dynamics model (i.e. RE-model) built for the purposes of this study is shown in Table 4 below. The endogenous variables are those that are determined endogenously in the RE-model with the use of equations. The exogenous variables refer to those data parameters considered in the model that are derived from external sources and are usually expressed as constants within the model simulation. The excluded variables are those that are considered for qualitative system dynamics modelling purposes (i.e. the causal-effect relationship usually expressed in the form of a causal loop diagram) but that have not been utilised in the model simulation for the purposes of the study. In short, the model boundary chart serves the purpose of setting out the delimitations to the study in order to portray which data parameters have been considered and what has been excluded for the purposes of the research. In this case, some variables considered within the qualitative system dynamics modelling were excluded because they were beyond the scope of the study.

**Table 4**  
The RE-model boundary chart

Endogenous variables	Exogenous variables	Excluded variables
Eucalyptus species regrowth	Discount rate	Active restoration
Number of diesel equivalent units	Elasticity of person days to budget	Area Illegally planted
Area invaded by <i>Pinus</i> species	Carbon Sequestration per ha <i>Acacia Saligna</i>	Delivery of electricity to the grid
Area invaded by <i>Eucalyptus</i> species	Carbon Sequestration per ha <i>Acacia Cyclops</i>	Electricity generation from hydro-electrical plants, solar energy, coal and other sources.
Annual IAP clearing	Biomass per ha <i>Acacia Saligna</i>	Emissions from Rooikrans power generation
Number of units	Electricity price	Fire cost
Person days	FINAL TIME	Fire incidence
<i>Acacia Cyclops</i> regrowth	Biomass conversion into Kw	Grazing capacity
<i>Acacia Cyclops</i> clearance	Factor correcting for net carbon	Happiness Index
Area cleared	Capacity utilisation factor	Human demographics
Area invaded by <i>Acacia Saligna</i>	Biomass per ha <i>Pinus</i> species	Impact on local economy
Budget DEA DH & DEA DH+	Carbon Sequestration per ha <i>Eucalyptus</i> species	Job creation
Area invaded by <i>Acacia Cyclops</i>	Biomass per ha <i>Eucalyptus</i> species	Passive restoration
<i>Eucalyptus</i> species clearance	Diesel emission factor	Restoration cost
Effect of person days (PD) on area cleared (ha)	Constant (ha)	Restoration rate
<i>Acacia Saligna</i> clearance	Biomass per ha <i>Acacia Cyclops</i>	Soil erosion
Emissions avoided	Conversion factor	Species abundance
Capital cost	Carbon sequestration per ha <i>Pinus</i> species	Training

continued/



Endogenous variables	Exogenous variables	Excluded variables
Emission value	Constant (PD)	Value Added Products (excluding Electricity)
Effect of budget on person days	Co-finance proportion	
Grand initial IAP area	Initial area invaded by <i>Acacia Cyclops</i>	
Net Carbon sequestrated	Initial area invaded by <i>Acacia Saligna</i>	
Net Carbon value	Initial area invaded by <i>Eucalyptus</i> species	
Net value of bio-electricity sales	Initial area invaded by <i>Pinus</i> species	
<i>Pinus</i> species clearance	INITIAL TIME	
<i>Pinus</i> species regrowth	Losses	
Power generation Rooikrans ( <i>Acacia Cyclops</i> ) Kw & Kwh	Profit margin ratio	
Present value factor	Spread rate <i>Acacia Cyclops</i>	
Proportion <i>Acacia Cyclops</i>	Spread rate <i>Acacia Saligna</i>	
Proportion <i>Acacia Saligna</i>	Spread rate <i>Eucalyptus</i> species	
Proportion <i>Eucalyptus</i> species	Spread rate <i>Pinus</i> species	
Proportion <i>Pinus</i> species	Unit capital cost	
Sequestrated carbon <i>Acacia Cyclops</i>	Unit price of carbon	
Sequestrated carbon <i>Acacia Saligna</i>	Unit variable cost	
Sequestrated carbon <i>Eucalyptus</i> species		
Sequestrated carbon sequestrated <i>Pinus</i> species		
Total variable cost		
Value of electricity sales		

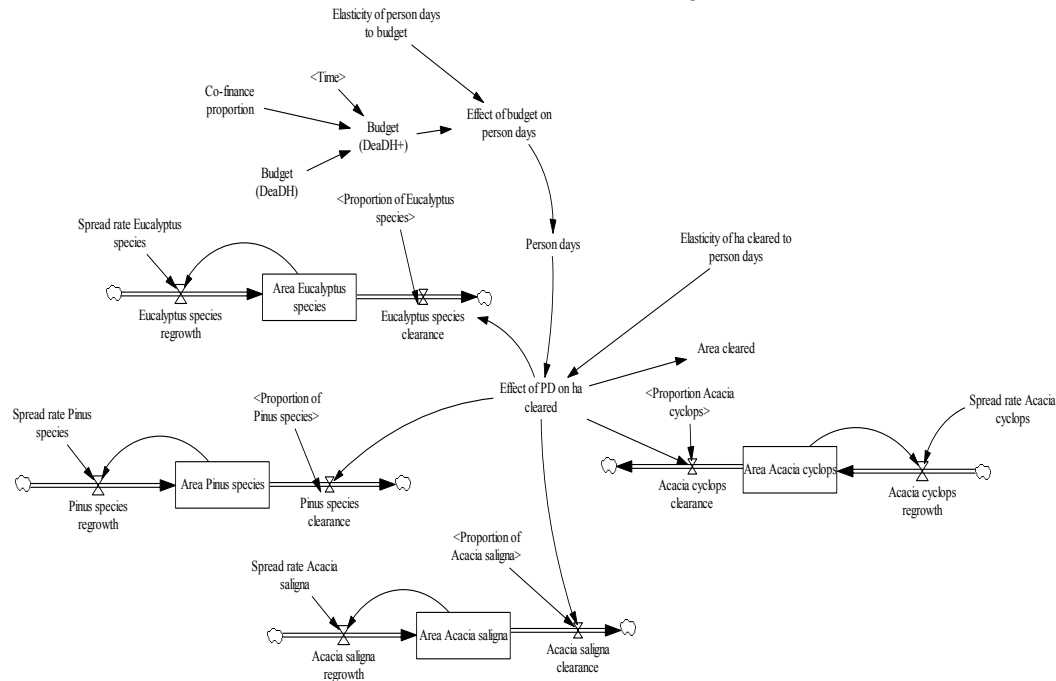
### 3.4 Model description

The RE-model models the potential electricity generation from Rooikrans woody biomass compared with electricity produced by diesel generators. The base year for the model is 2014 and it is assumed that the biomass gasification plant will be constructed and will become fully-operational in the year 2016. The RE-model runs from 2014 to 2030. It consists of five sub-models: a land-use sub-model, a clearing cost sub-model, a carbon sequestration sub-model, an economic sub-model and the power generation sub-model.

The land-use sub-model models the land-use patterns by the major IAPs in the De Hoop area. The structure of this sub-model is shown in Figure 3.

This sub-model consists of four stock variables. That is, the area invaded by *Acacia Cyclops* (Rooikrans), the area invaded by *Acacia Saligna*, the area invaded by *Eucalyptus* spp. and the area invaded by *Pinus* spp. The parameters used in this sub-model are shown in Table 5. The area invaded by *Acacia Cyclops* (AIAC, ha) is increased by regrowth (ACR, ha/year) which is reduced by clearing (ACC, ha/year) undertaken by WfW. This clearing (ACC, ha/year) is influenced by the effect on person days for hectares cleared (EPDHC, ha/year) minus the constant (K, ha) and then divided by the proportion of *Acacia Cyclops* (PAC, Dmnl). The proportion of *Acacia Cyclops* and the effect on person days on hectares cleared are shadow variables in this sub-model. These variables link with the *Acacia Cyclops* clearing variable and the land-use sub-model in a different way. The same scenario happens for all the other stock variables. This study is concerned with Rooikrans, so the biomass from Rooikrans will be used for power generation. The uses of the other stock variables are beyond the scope of this paper. Additionally, the respective complete equations used in the land-use sub-model are shown in the Appendix.

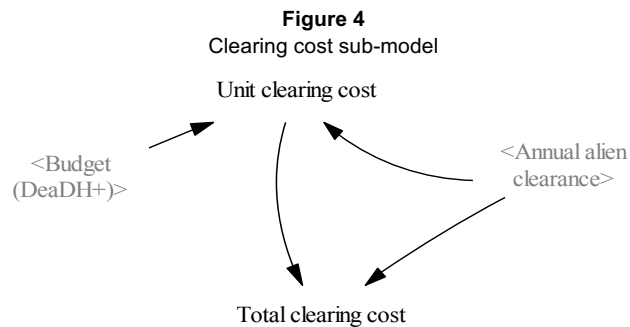
**Figure 3**  
Land use sub-model stock and flow diagram



**Table 5**  
Parameters used in the land-use sub-model

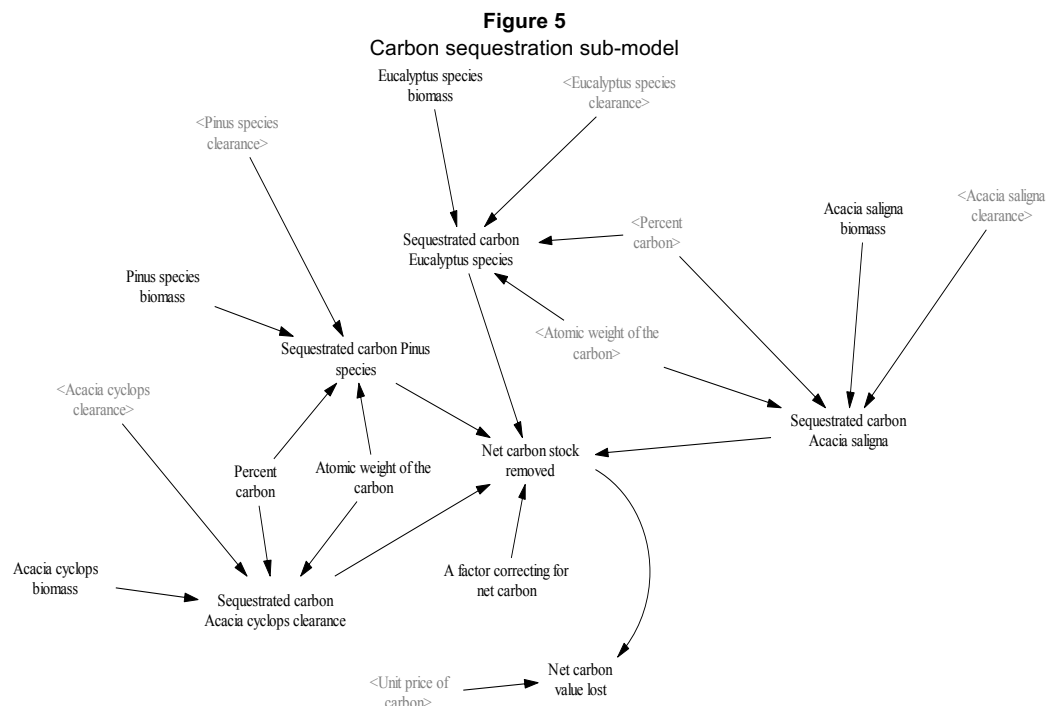
Description	Formula/value	Unit	Reference	Comment
Co-finance proportion	1	Dmnl	Policy variable	
Elasticity of person days to budget	0.0049	PD/ZAR	Own calculation	
Spread rate <i>Eucalyptus</i> spp.	0.15	Dmnl/year	Van Wilgen & Le Maitre (2013)	Conservative estimate for annual spread rate
Spread rate <i>Pinus</i> spp.	0.15	Dmnl/year	Van Wilgen & Le Maitre (2013)	Conservative estimate for annual spread rate
Spread rate <i>Acacia Saligna</i>	0.15	Dmnl/year	Van Wilgen & Le Maitre (2013)	Conservative estimate for annual spread rate
Spread rate <i>Acacia Cyclops</i>	0.15	Dmnl/year	Van Wilgen & Le Maitre (2013)	Conservative estimate for annual spread rate
Initial area <i>Acacia Cyclops</i>	3555.71	ha	Kotzé et al. (2010)	Based on the national invasive alien plant survey
Initial area <i>Acacia Saligna</i>	233.75	ha	Kotzé et al. (2010)	Based on the national invasive alien plant survey
Initial area <i>Eucalyptus</i> spp.	44.34	ha	Kotzé et al. (2010)	Based on the national invasive alien plant survey
Initial area <i>Pinus</i> spp.	279.56	ha	Kotzé et al. (2010)	Based on the national invasive alien plant survey

The clearing cost sub-model models the total cost of clearing the major IAPs (i.e. *Acacia Cyclops*, *Acacia Saligna*, *Pinus* spp. and *Eucalyptus* spp.) in the De Hoop nature reserve. This sub-model is illustrated in Figure 4.



The total clearing cost is the product of the unit clearing costs and the total annual clearance of all the major IAPs in the De Hoop area. The unit clearing cost is derived by dividing the total budgeted amount (DEADH+) by the total annual IAP clearance for all the IAPs in the De Hoop nature reserve. The budgeted amount is influenced by the co-finance proportion, DEADH budget and the time factor. The annual IAP clearance and the budgeted amount (DEADH+) are shadow variables affecting the total clearing cost in a way that differs from the other variables.

The carbon sequestration sub-model models the externality benefit of IAPs using carbon during the photosynthesis process and reducing greenhouse gases in the atmosphere. This sub-model is depicted in Figure 5.



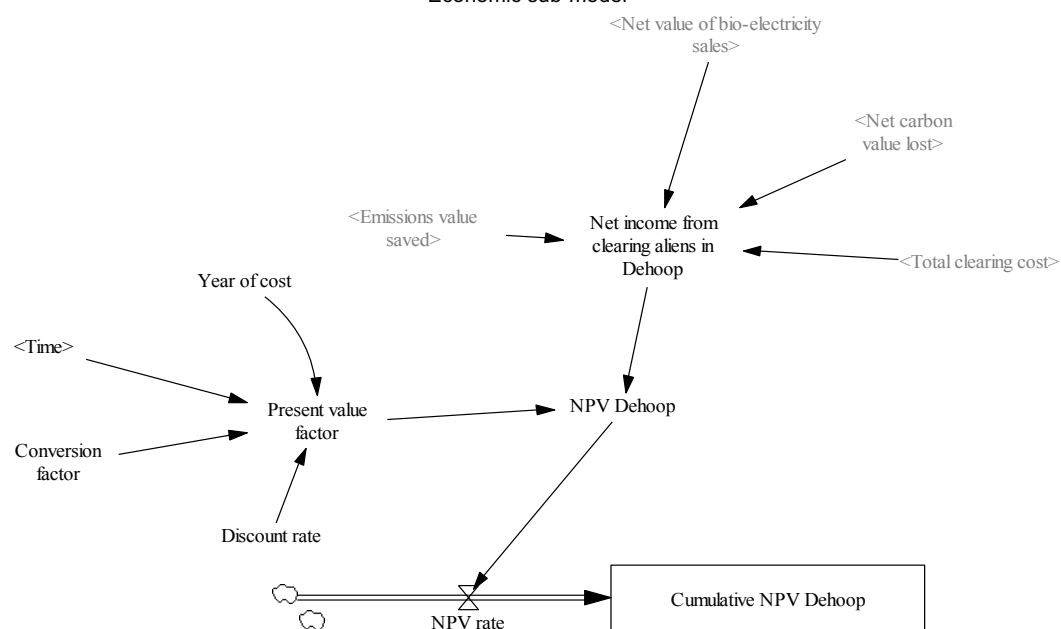
There are five parameters used in this sub-model (see Table 6) showing the value of carbon sequestration per hectare cleared of all the major IAPs. These parameters are given in greater detail in the Appendix. Each hectare cleared (of the major IAPs) decreases the quantity of the sequestered carbon by the respective IAPs. The unit price of carbon is also one of these parameters and is an exogenous policy variable derived from the Carbon Tax policy of South Africa which is then multiplied by the net carbon loss to give a monetary value of the negative externality incurred as a result of clearing the respective IAPs in the De Hoop nature reserve.

**Table 6**  
Parameters used in the carbon sequestration sub-model

Description	Formula/ value	Unit	Reference	Comment
Carbon sequestration per ha <i>Pinus</i> spp.	74.25675	tC/ha	Mugido et al. (2013) & Thomas and Martin (2012)	(45%×total condensed biomass/ha)×3.6667 Note: 55% moisture content is removed to be left with the 45% oven dry mass. Additionally, 3.6667 is the ratio of CO <sub>2</sub> over carbon.
Carbon sequestration per ha <i>Eucalyptus</i> spp.	93.3578487	tC/ha	Mugido et al. (2013) & Thomas & Martin (2012)	(45%×total condensed biomass/ha)×3.6667 Note: 55% moisture content is removed to be left with the 45% oven dry mass. Additionally, 3.6667 is the ratio of CO <sub>2</sub> over carbon.
Carbon sequestration per ha <i>Acacia Saligna</i>	38.280348	tC/ha	Mugido et al. (2013) & Thomas & Martin (2012)	(45%×total condensed biomass/ha)×3.6667 Note: 55% moisture content is removed to be left with the 45% oven-dry mass. Additionally, 3.6667 is the ratio of CO <sub>2</sub> over carbon.
Carbon sequestration per ha <i>Acacia Cyclops</i>	93.3578487	tC/ha	Mugido et al. (2013); Thomas & Martin (2012)	(45%×total condensed biomass/ha)×3.6667 Note: 55% moisture content is removed to be left with the 45% oven dry mass. Additionally, 3.6667 is the ratio of CO <sub>2</sub> over carbon.
Unit price of carbon	120	ZAR/tC	National Treasury (2013)	Based on the carbon tax policy rate.

The economic sub-model is shown in Figure 6 and gives the modelled cost-benefit analysis criterion adopted in this study, which is the net present value (NPV).

**Figure 6**  
Economic sub-model



There are two parameter variables in this sub-model, that is, the conversion factor and the discount rate (see Table 7). The NPV is influenced by these model parameters as well as by the time factor and the year of the cost variables. The NPV factor is derived by summing the conversion factor

Description	Formula/value	Unit	Reference	Comment
Conversion factor	1	Dmnl	Policy variable	
Discount rate	0.06	Dmnl	Policy variable	Based on the National Treasury rates

Description	Formula/value	Unit	Reference	Comment
Conversion factor	1	Dmnl	Policy variable	
Discount rate	0.06	Dmnl	Policy variable	Based on the National Treasury rates

[illegible]

The biomass conversion into kilowatt (kW) energy influences the number of units required to produce electricity from Rooikrans woody biomass (i.e. the number of System Johansen Gasifier units required = ((Total biomass/Biomass conversion into kW)/1000)/Size of biomass generator) and also the power generation from Rooikrans (i.e. power generation kW= (Total biomass/Biomass conversion into kW). The number of units required to produce electricity from Rooikrans biomass is influenced by total woody biomass (which is a function of Rooikrans biomass per hectare and the Rooikrans clearance) in conjunction with the biomass conversion into electricity.

**Table 8**  
Parameters used in power generation sub-model

Description	Formula/value	Unit	Reference	Comment
Biomass conversion into kW	14	t/kW	Stafford et al. (2016)	
Total hours per year	8760	h	Stafford et al. (2016)	
Diesel emission factor	100	tC/kWh	Stafford et al. (2016)	
Unit value of carbon	120	ZAR/ton	National Treasury (2013)	Based on the carbon tax policy rate
Capacity utilisation factor	0.8	Dmnl	Stafford et al. (2016)	
Unit variable cost	5 866 330	ZAR	Stafford et al. (2016)	
Electricity price	1.60	ZAR	Stafford et al. (2016)	
Unit capital cost	33 765 700	ZAR	Stafford et al. (2016)	
Size of biomass generator	0.8	MWe	Stafford et al. (2016)	

In addition, the number of units required for electricity generation influences the number of equivalent diesel units, the total variable cost and the capital cost. The capital cost and the total variable cost (together with the value of electricity sales) affect the net value of electricity sales, which is derived by subtracting the total costs (i.e. capital costs and the variable costs) from the value of electricity sales. The power generation from Rooikrans biomass per hour produced by the units is then calculated by the power generation of Rooikrans, the annual time during which the electricity plant runs and the capacity utilisation factor. The power generation from Rooikrans biomass per hour together with the diesel emission factor then influences the diesel emissions avoided. This affects the emission value, which is derived from the product of diesel emissions avoided and the unit value of carbon.

The comprehensive model equations used in the five sub-models of the RE-model are presented in Table 12 in the Appendix.

## 4 Results

### 4.1 Model scenarios and sensitivity analysis

The RE-model was run for three scenarios to test for uncertainties about the anticipated outcomes of the system dynamics model and its implications for policy- and decision-makers. In the first scenario (DEA DH), the clearing operations were funded by the Department of Environmental Affairs budget alone, the second scenario (DEA DH+) involved funding for clearing operations by the DEA and a co-finance option of 20 per cent from the private sector. The third scenario was the baseline case, which is the do nothing scenario. The three scenarios considered in this study are shown in Table 9.

**Table 9**  
Scenarios considered in this study

Scenario	Brief description
1. DEA DH	No clearing of Rooikrans for the period 2008–2016. The bio-electricity plant is to be constructed in 2016 and electricity production will start in 2017. Clearing operations will commence in 2017, using the DEA budget only (i.e. no co-finance).
2. DEA DH+	No clearing of Rooikrans for the period 2008–2016. The bio-electricity plant is to be constructed in 2016 and electricity production will start in 2017. Clearing operations commence in 2017, using the DEA budget and 20% co-finance from the private sector.
3. Baseline case: Do nothing DEA DH	Baseline scenario: Clearing operations are to be done from 2008–2016 and after that there will be no clearing of Rooikrans. Additionally, no bio-electricity plant is set up.

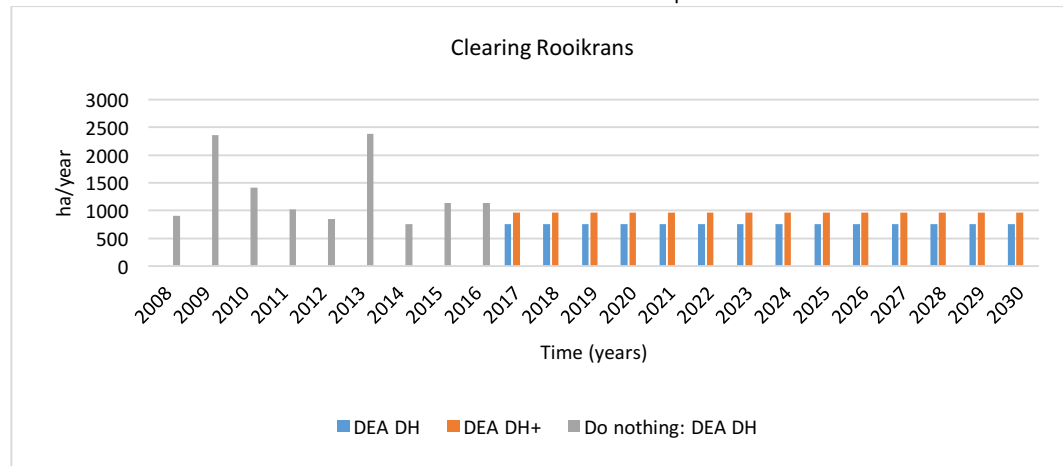
### 4.2 Clearing Rooikrans

The RE-model results show that the areas cleared per annum for the scenarios remained constant at 753.6006 hectares (Scenario 1) and 965.2275 hectares (Scenario 2). Additionally, the same annual clearing figures for the baseline scenario (Scenario 3) were observed per annum. The outcomes of clearing Rooikrans produced by the RE-model are shown in Figure 8. Basically,



clearing Rooikrans is a function of person days worked by the clearing teams, which, in turn, is a function of the DEA DH and DEA DH+ budgets.

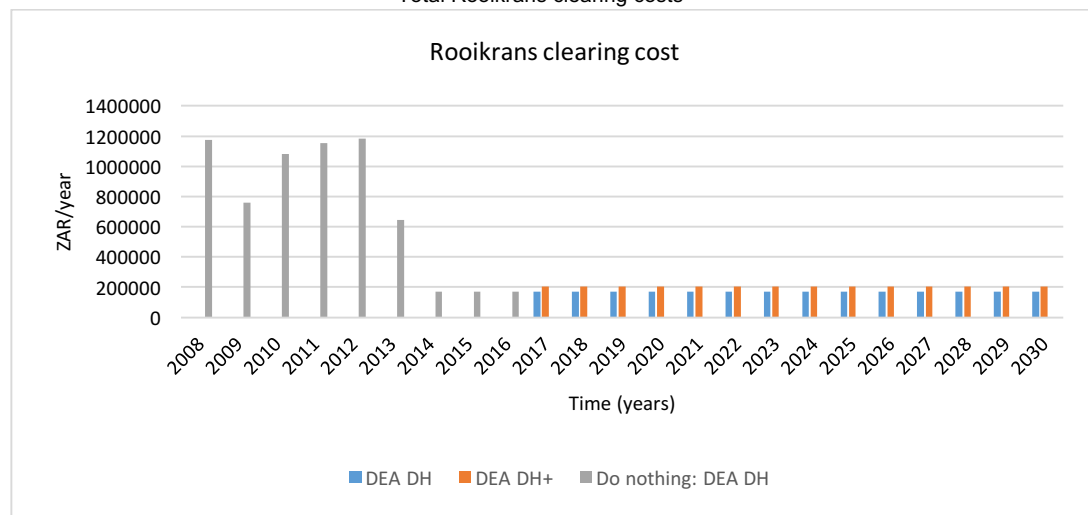
**Figure 8**  
The area cleared of Rooikrans in the De Hoop nature reserve



#### 4.3 Total Rooikrans clearing cost

The clearing costs for the DEA DH and DEA DH+ scenarios (Scenarios 1 and 2) were assumed to be zero for the period 2008–2016, as the Systems Johansen Gasifier units (i.e. the bio-electricity power plant) was set up only in 2016 to be operational in 2017. The annual clearing cost values for these scenarios are the same and will be constant from 2017–2030, as illustrated in Figure 9. The clearing costs for the baseline scenario (Scenario 3) are zero for 2017–2030 because it is assumed that no bio-electricity plant will have been set up and therefore, no clearing will be done.

**Figure 9**  
Total Rooikrans clearing costs

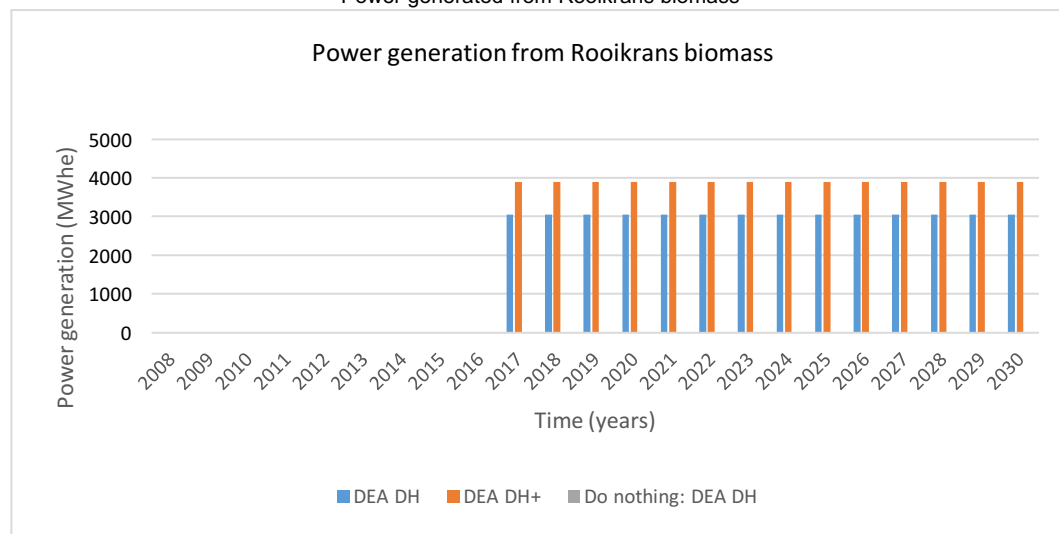


#### 4.4 Rooikrans electricity generation

The results from the RE-model show that the electricity generated per annum remains constant from the beginning of the electricity production, using the Systems Johansen Gasifier units to the

end of the model simulation (2017–2030). The total electricity generated from Rooikrans is approximately 3 045.623 MWh per annum for the DEA DH scenario (Scenario 1). The total generation from both the DEA DH+ scenario (Scenario 2) is the same at 3 900.898 MWh per year. As for the base case scenario (Scenario 3), no electricity will be produced because it is assumed that no bio-electricity plant will be set up. The general output for the Rooikrans electricity generation for all three scenarios is shown in Figure 10.

**Figure 10**  
Power generated from Rooikrans biomass



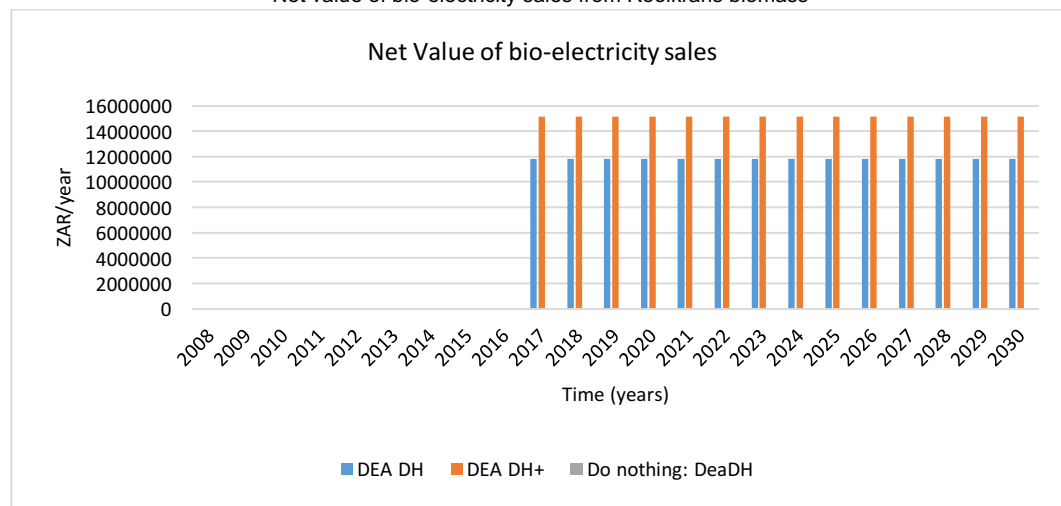
#### 4.5 Emissions avoided and saved owing to Rooikrans bio-electricity production

The RE-model shows that, as a result of using Rooikrans biomass to produce electricity, greenhouse gas emissions avoided and saved unlike with the use of electricity generation by diesel generators. The bio-electricity plant emits fewer greenhouse gases in comparison with diesel generators, thus leading to a low carbon footprint. If diesel generators were used rather than the Systems Johansen Gasifier units, 12 806.24 tonnes of carbon would be emitted per annum under the DEA DH scenario (Scenario 1). Additionally, following the DEA DH+ scenario, 16 402.5 tonnes of carbon would be emitted per annum by diesel generators. However, in the base line scenario, there are no greenhouse gas emissions. The RE-model further shows that the bio-electricity generation would lead to saving greenhouse gas emissions. Under the DEA DH scenario (Scenario 1), ZAR4 763 531 worth of carbon per annum could be saved, while ZAR6 108 950 per annum could be saved in the DEA DH+ scenario (Scenario 2). In the case of the baseline scenario, there are no greenhouse gas emissions.

#### 4.6 Net value of Rooikrans bio-electricity sales

The RE-model shows that the net value of electricity sales produced using the Systems Johansen Gasifier units is worth ZAR1 1,8 million per annum for the DEA DH scenario (Scenario 1) for 2017–2030. The net value of electricity sales in the DEA DH+ scenario (Scenario 2) is ZAR15, 1million per annum for 2017–2030. The value under the base case scenario (Scenario 3) is zero for the entire simulation period owing to the absence of a bio-electricity plant. Additionally, the net value of electricity sales under all scenarios remains constant over the entire study period. The output for the net value of electricity sales is illustrated in Figure 11.

**Figure 11**  
Net value of bio-electricity sales from Rooikrans biomass



#### 4.8 Net carbon stock removed and value lost owing to clearing Rooikrans

The clearing of Rooikrans in the De Hoop nature reserve results in the loss of standing carbon stock. Further, a carbon value is also lost as result of the loss in carbon sequestration which was performed by the Rooikrans trees before clearing. The RE-model shows that under the DEA DH scenario (Scenario 1), approximately 38 763.84 tonnes of carbon stock will be lost per annum for 2017–2030, while approximately 49 649.54 tonnes of carbon stock per annum are removed under the DEA DH+ scenario for the study period (Scenario 2). As for the base case scenarios (Scenario 3), the net carbon stock is zero as no bio-electricity plant is set up. In monetary terms, approximately ZAR4 651 661 is lost per annum as a result of clearing Rooikrans in the De Hoop nature reserve under the DEA DH scenario (Scenario 1). Under the DEA DH+ scenario (Scenario 2) approximately ZAR5,9million is lost per annum owing to clearing Rooikrans in the De Hoop nature reserve. As for the base case (Scenario 3), no carbon stock is removed and no value is lost for the study period.

#### 4.9 Net income from Rooikrans bio-electricity production

The RE-model shows that the net income realised from the Rooikrans bio-electricity production is approximately ZAR8,5 million per annum for DEA DH scenario (Scenario 1) for 2017–2030. Under the DEA DH+ scenario (Scenario 2), the net income is roughly ZAR10,9 million per annum within the same period. The opportunity cost of income forgone because electricity is not produced in the base case scenario varies between 2008 and 2016 (see Table 9). However, for 2017–2030, this opportunity cost becomes zero for the base case scenario, as no bio-electricity plant was set up. The output from the RE-model on net income from bio-electricity production is presented in Table 10.

**Table 10**  
Net income from Rooikrans bio-electricity production

year	DEA DH (ZAR/year)	DEA DH+ (ZAR/year)	Baseline Case: Do nothing (ZAR/year)
2008	0	0	-6 753 034,5
2009	0	0	-15 351 262
2010	0	0	-9 814 250

*continued/*

year	DEA DH (ZAR/year)	DEA DH+ (ZAR/year)	Baseline Case: Do nothing (ZAR/year)
2011	0	0	-7 497 931
2012	0	0	-6 420 332,5
2013	0	0	-15 390 586
2014	0	0	-4 822 670,5
2015	0	0	-7 205 453
2016	0	0	-7 205 453
2017	8 530 754	10 940 192	0
2018	8 530 754	10 940 192	0
2019	8 530 754	10 940 192	0
2020	8 530 754	10 940 192	0
2021	8 530 754	10 940 192	0
2022	8 530 754	10 940 192	0
2023	8 530 754	10 940 192	0
2024	8 530 754	10 940 192	0
2025	8 530 754	10 940 192	0
2026	8 530 754	10 940 192	0
2027	8 530 754	10 940 192	0
2028	8 530 754	10 940 192	0
2029	8 530 754	10 940 192	0
2030	8 530 754	10 940 192	0

#### 4.10 Cumulative net present value for the Rooikrans bio-electricity power plant

The RE-model results show a positive NPV value for all the scenarios except for the base case scenario, which is negative. The cumulative NPV for the DEA DH scenario (Scenario 1) is approximately ZAR44,7 million for 2017–2030 while the cumulative NPV for the DEA DH+ scenario (Scenario 2) is approximately ZAR57,3 million. For the base case scenario (Scenario 3), the cumulative NPV is approximately -ZAR61,8 million. The output of the RE-model regarding the cumulative NPV for bio-electricity production is presented in Table 11.

**Table 11**  
Cumulative NPV for bio-electricity using Rooikrans woody biomass

Year	DEA DH (ZAR/year)	DEA DH+ (ZAR/year)	Baseline Case: Do nothing (ZAR/year)
2008	0	0	0
2009	0	0	-6 370 787,5
2010	0	0	-20 033 358
2011	0	0	-28 273 592
2012	0	0	-34 212 656
2013	0	0	-39 010 304
2014	0	0	-49 860 064
2015	0	0	-53 067 416
2016	0	0	-57 588 208
2017	0	0	-61 853 108
2018	4 763 531	6 108 949,5	-61 853 108
2019	9 257 428	11 872 110	-61 853 108
2020	13 496 954	17 309 054	-61 853 108
2021	17 496 508	22 438 246	-61 853 108
2022	21 269 672	27 277 108	-61 853 108

*continued/*

2023	24 829 260	31 842 072	-61 853 108
2024	28 187 362	36 148 640	-61 853 108
2025	31 355 384	40 211 440	-61 853 108
2026	34 344 084	44 044 272	-61 853 108
2027	37 163 612	47 660 152	-61 853 108
2028	39 823 544	51 071 360	-61 853 108
2029	42 332 916	54 289 480	-61 853 108
2030	<b>44 700 248</b>	<b>57 325 444</b>	<b>-61 853 108</b>

## 5 Discussion

Given the results produced by the RE-model (as presented in Section 4), the evidence suggests that the production of electricity using Rooikrans woody biomass with the Systems Johansen gasifier units is economically viable. In comparison with the electricity generated by diesel generators, the greenhouse gas emissions emanating from the System Johansen gasifier units are much lower. Approximately 12 806.24 and 16 402.5 tonnes of carbon are emitted by diesel generators per annum in the simulated Scenarios 1 and 2, respectively, and as a result of switching from diesel generators to a bio-electricity plant, approximately ZAR4,7million and ZAR6,1million of carbon dioxide emissions will be saved per annum. This money could then be used to fund programmes or projects that aim to reduce the carbon footprint of activities like electricity generation, as well as other pro-conservation initiatives.

The results produced by the RE-model regarding clearing the Rooikrans shows that the areas cleared are similar and constant over the entire simulation. This is because the spread rates did not affect the RE-model as it is concerned only with the clearing and electricity generation from the cleared Rooikrans biomass. The spread rates, however, do have an influence on the re-growth of Rooikrans, but this was beyond the scope of this study. The same can be seen in all the other results in the various scenarios (Section 4), which can be for the same reason.

Having discounted the net income flows with a discount rate of 6 per cent, the cumulative NPV for generating electricity from Rooikrans biomass using the Systems Johansen gasifier units was positive for all the scenarios, except for the base case scenario, which resulted in a negative value. The rule of thumb in a cost-benefit analysis is that projects yielding a positive NPV are preferable, and those with a negative NPV should be avoided. The DEA DH+ scenario (Scenario 2) shows the highest positive cumulative NPV of ZAR57,3 million, followed by the DEA DH scenario (Scenarios 1) with a positive cumulative NPV of ZAR44,7 million. Lastly, the base case scenario has a negative cumulative NPV of -ZAR61,8 million. Given this situation, Scenarios 1 and 2 are favourable, while Scenario 3 is the worst-case scenario. Decision-makers should pay exclusive attention to Scenarios 1 and 2, giving Scenario 2 the highest priority. The 'do nothing' scenario has a negative NPV and poses an opportunity cost to the De Hoop society, as there is no bio-electricity plant. Decision-makers should therefore not consider this scenario at all.

## 6 Conclusion

The results of this study show that there is great potential for using Rooikrans biomass as feedstock for electricity generation rather than electricity generation by diesel generators. Despite IAPs like Rooikrans being a major disturbance in the De Hoop nature reserve, there are benefits that accrue as a result of transforming the IAP biomass into value-added products. This study showed empirically that, if Rooikrans biomass is used to produce electricity, various benefits will be realised by the De Hoop community, such as power generation, that is, price competitive, reduced carbon emissions, net carbon value savings, a low carbon footprint, and income generation from bio-electricity sales. Furthermore, the construction of the bio-electricity plant could potentially create more employment in the De Hoop area, as people would be needed to work in the power plant. This would, in turn, have multiple effects on the economy, leading to more electricity and less pressure on the national ESKOM grid, thereby positively affecting other

electricity users owing to reduced load-shedding risks. Policy-makers should view the generation of electricity using IAP biomass (such as Rooikrans) as an option that would help solve the South African electricity crisis and reduce the carbon footprint caused by electricity generation from fossil fuels like coal and diesel. It is important to note that the cost-benefit analysis results presented in this study are not a one-size-fits-all, so other methods should be used to evaluate and test the various options faced by the decision-makers. Further study is required to investigate the feasibility of Rooikrans in comparison with other IAPs.

#### Endnote

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## Appendix

### A1. Equations used in the RE-model

**Table 12**  
Equations used in the five sub-models of the RE-model

Description	Formula/value	Unit	Reference	Comment
<i>Acacia cyclops</i> (Rooikrans) clearance	(Effect of PD on ha cleared-10250)*Proportion <i>Acacia cyclops</i>	ha/year	Own calculation	
<i>Acacia cyclops</i> regrowth	Area <i>Acacia cyclops</i> *Spread rate <i>Acacia cyclops</i>	ha/year	Own calculation	
<i>Acacia Saligna</i> clearance	Effect of PD on ha cleared-10250)*Proportion of <i>Acacia Saligna</i>	ha/year	Own calculation	
<i>Acacia Saligna</i> regrowth	Area <i>Acacia Saligna</i> *Spread rate <i>Acacia Saligna</i>	ha/year	Own calculation	
Annual alien clearance	<i>Acacia cyclops</i> clearance + <i>Acacia Saligna</i> clearance+ <i>Eucalyptus</i> species clearance+ <i>Pinus</i> species clearance	ha/year	Own calculation	
Area <i>Acacia cyclops</i>	INTEG ( <i>Acacia cyclops</i> regrowth- <i>Acacia cyclops</i> clearance, Initial area <i>Acacia cyclops</i> )	ha	Own calculation	
Area <i>Acacia Saligna</i>	INTEG ( <i>Acacia Saligna</i> regrowth- <i>Acacia Saligna</i> clearance, Initial area <i>Acacia Saligna</i> )	ha	Own calculation	
Area cleared	Effect of PD on ha cleared-10250	ha/year	Own calculation	
Area <i>Eucalyptus</i> species	INTEG ( <i>Eucalyptus</i> species regrowth- <i>Eucalyptus</i> species clearance, Initial area <i>Eucalyptus</i> species)	ha	Own calculation	
Area <i>Pinus</i> species	INTEG ( <i>Pinus</i> species regrowth- <i>Pinus</i> species clearance, Initial area <i>Pinus</i> species)	ha	Own calculation	
"Budget (DeaDH+)"	"Co-finance proportion***Budget (DeaDH)"(Time)	ZAR/year	Own calculation	
Capital cost	Number of units*Unit capital cost)*A factor correcting for once capital cost (Time)	ZAR/year	Own calculation	
Cumulative invaded area	Area <i>Acacia cyclops</i> (Rooikrans) + Area <i>Acacia Saligna</i> +Area <i>Eucalyptus</i> species +Area <i>Pinus</i> species	ha	Own calculation	
Cumulative NPV De Hoop	INTEG (NPV rate, 0)	ZAR	Own calculation	
Effect of budget on person days	Elasticity of person days to budget**Budget (DeaDH+)"	PD/year	Own calculation	
Effect of PD on ha cleared	Elasticity of ha cleared to person days*LN(Person days)	ha/year	Own calculation	
Emissions avoided	Power generation Rooikrans kWh*Diesel emission factor	ton/year	Own calculation	
Emissions value saved	Emissions avoided*Unit price of carbon	ZAR/year	Own calculation	
<i>Eucalyptus</i> species clearance	(Effect of PD on ha cleared-10250)*Proportion of <i>Eucalyptus</i> species	ha/year	Own calculation	
<i>Eucalyptus</i> species regrowth	Area <i>Eucalyptus</i> species*Spread rate <i>Eucalyptus</i> species	ha/year	Own calculation	

continued/

Description	Formula/value	Unit	Reference	Comment
FINAL TIME	2030	year	Own calculation	The final time for the simulation
Grand initial alien area	Initial area <i>Acacia cyclops</i> (Rooikrans) +Initial area <i>Eucalyptus</i> species + initial area <i>Pinus</i> species+ Initial area <i>Pinus</i> Species + Initial area <i>Acacia Saligna</i>	ha	Own calculation	
Net carbon stock removed	(Sequestered carbon <i>Eucalyptus</i> species+ Sequestered carbon <i>Pinus</i> species +Sequestered carbon <i>Acacia cyclops</i> clearance +Sequestered carbon <i>Acacia Saligna</i> )*A factor correcting for net carbon	ton/year	Own calculation	
Net carbon value lost	Unit price of carbon*Net carbon stock removed	ZAR/year	Own calculation	
Net income from clearing aliens in De Hoop	("Net value of bio-electricity sales" +Emissions value saved)-Net carbon value lost-Total clearing cost	ZAR/year	Own calculation	
"Net value of bio-electricity sales"	Value of electricity sales-Total variable cost-Capital cost	ZAR/year	Own calculation	
NPV De Hoop	Net income from clearing aliens in De Hoop/Present value factor	ZAR/year	Own calculation	
NPV rate	NPV De Hoop	ZAR/year	Own calculation	
Number of diesel equivalent units	(Number of units/0.63)*A factor correcting for variable cost (Time)	Dmnl	Own calculation	
Number of units	((Total biomass/Biomass conversion into kW)/1000)/Size of biomass generator	Dmnl	Own calculation	
Person days	Effect of budget on person days-315.26	PD/year	Own calculation based on DEA-NRM (2015)	
<i>Pinus</i> species clearance	(Effect of PD on ha cleared-10250)*Proportion of <i>Pinus</i> species	ha/year	Own calculation based on DEA-NRM (2015)	
<i>Pinus</i> species regrowth	Area <i>Pinus</i> species*Spread rate <i>Pinus</i> species	ha/year	Own calculation	
Power generation Rooikrans kW	(Total biomass/Biomass conversion into kW)	kW/year	Own calculation	
Power generation Rooikrans kWh	(Power generation Rooikrans kW*Total hours per year)*Capacity utilization factor	kWh/year	Own calculation	
Present value factor	((Conversion factor+ Discount rate)^Year of cost(Time))	Dmnl	Own calculation	
Proportion <i>Acacia cyclops</i> (Rooikrans)	Initial area <i>Acacia cyclops</i> /Grand initial alien area	Dmnl	Own calculation	
Proportion of <i>Acacia Saligna</i>	Initial area <i>Acacia Saligna</i> /Grand initial alien area	Dmnl	Own calculation	
Proportion of <i>Eucalyptus</i> species	Initial area <i>Eucalyptus</i> species/Grand initial alien area	Dmnl	Own calculation	
Proportion of <i>Pinus</i> species	Initial area <i>Pinus</i> species/Grand initial alien area	Dmnl	Own calculation	
SAVEPER	TIME STEP	year	Own calculation	The frequency with which output is stored
Sequestered carbon <i>Acacia cyclops</i> (Rooikrans) clearance	<i>Acacia cyclops</i> biomass* <i>Acacia cyclops</i> clearance*Percent carbon*Atomic weight of the carbon	ton/year	Own calculation	
Sequestered carbon <i>Acacia Saligna</i>	<i>Acacia Saligna</i> biomass* <i>Acacia Saligna</i> clearance*Percent carbon*Atomic weight of the carbon	ton/year	Own calculation	
Sequestered carbon <i>Eucalyptus</i> species	<i>Eucalyptus</i> species biomass* <i>Eucalyptus</i> species clearance*Percent carbon*Atomic weight of the carbon	ton/year	Own calculation	
Sequestered carbon <i>Pinus</i> species	<i>Pinus</i> species biomass* <i>Pinus</i> species clearance*Percent carbon*Atomic weight of the carbon	ton/year	Own calculation	
Total biomass	<i>Acacia cyclops</i> clearance*Biomass per ha <i>acacia cyclops</i>	ton/year	Own calculation	
Total clearing cost	Unit clearing cost*Annual alien clearance	ZAR/year	Own calculation	
Total variable cost	(Number of units*Unit variable cost)*A factor correcting for variable cost (Time)	ZAR/year	Own calculation	
Unit clearing cost	"Budget (DeaDH+)"/Annual alien clearance	ZAR/ha	Own calculation	
Value of electricity sales	(Electricity price*Power generation rooikrans kWh)*A factor correcting for variable cost (Time)	ZAR/year	Own calculation	
Year of cost	[(2008,1)-(2030,23)]	Dmnl	Own calculation	The time period of the simulation

## A2. RE-model validation

### a) Model validation

Model validation is a continuous series of actions of checking and instituting confidence in a system dynamics model and this happens throughout the entire process of model building (Forrester & Senge, 1980). Since models are simple in nature showing presentations of real life situations, it is not possible to completely validate them (Sterman, 2000). Furthermore, no particular test can verify a model in totality, however the confidence in a model improves as the model passes a range of tests (Forrester & Senge, 1980). Forrester (1961) mentions that model validation needs to be judged with reference to a particular purpose. This is imperative for system dynamics models, since they are built to achieve a specific objective. The validation of the internal structure of the model comes first in system dynamics modelling, followed by behaviour validity, since the accuracy of model behaviour is meaningful only once adequate confidence on model structure has been established in advance (Barlas, 1994)

### b) Structural validity

Structural validity establishes the validity of the internal structure of the model through comparing model structure with either knowledge of the real system or general knowledge about the system as evidenced by literature (Barlas, 1994). Four direct structure validation tests, as introduced by Forrester and Senge (1980) for system dynamics, were conducted in this paper.

#### (i) Structure verification test

This test seeks to build model structure that imitates the real world situation reported in literature. It checks whether the model structure does not contradict with the available data of the real system being modelled (Forrester & Senge, 1980). In this case, the structure verification was two pronged. Firstly, South Africa specific data was used to construct the causal loop diagram, inter alia available knowledge about the real system in the literature. The causal relationships of the model were set up according to available data and information of the real world system being modelled to serve as a form of empirical structure validation (Zebda, 2002). Secondly, the validity of each of the model equations against available information and data was determined through the direct comparison of the respective model equations used to imitate the real world system and with general knowledge of the system described in literature (see Table 13).

**Table 13**  
Structure test for the RE-model

Model equation	Available knowledge on real system
Area Rooikrans (i.e. <i>Acacia Cyclops</i> ) species = Initial area Rooikrans + $\int$ (Rooikrans species regrowth - Rooikrans species clearance)dt	At any given time the "Area Rooikrans species" is the area that is invaded by Rooikrans species and is a function of the initial stock of Rooikrans species, Rooikrans species regrowth and Rooikrans species clearance.
Net income from clearing Rooikrans in Dehoop = ("Net value of bio-electricity sales" + Emissions value saved) - Net carbon value lost - Total clearing cost	The net income of any project is given by the difference between the cash inflows and cash outflows. In this study the net incomes are before tax deductions.

#### (ii) Dimensional consistency test

The dimensional consistency test seeks to establish the unit uniformity of all model equations. This means that, for each model equation, the unit of measure used for all the variables in the RE-Model, must be dimensionally consistent whilst excluding the scaling parameters that have no meaning in the context of the real world system (Sterman, 2000). The measurement units of input variables of all model equations used in the RE-Model, were inspected and found to be dimensionally consistent.

#### (iii) Parameter verification test

The parameter verification test consists of the conceptual and numerical evaluation of constant parameters of the model contrary to information pertaining the real system. The reason for

conducting this type of test in system dynamics modelling is to check and ensure the consistency of the model parameters counter to the system's descriptive and numerical data (Forrester & Senge, 1980). The values allocated to the RE-model parameters were obtained from existing data of the system, coupled with available numerical data on IAPs in South Africa. The parameters used in the RE-model are shown in Section 3.1.

(iv) *Extreme condition test*

This test seeks to assign extreme values to selected parameters, *inter alia*, the plausibility of the model generated behaviour against the envisaged scenarios of what may happen in comparable conditions in real life situations. In order for the systems dynamic model to pass this test, it must explicitly show the logical behaviour under extreme conditions (Forrester & Senge, 1980). An extreme condition test called Extreme condition test 1 was conducted. In extreme condition test 1, the budget was set to zero, which in reality means no investment into clearing activities, thus the total clearing cost becomes zero, invasive alien plant clearance (e.g. *Acacia cyclops* (Rooikrans) clearance) becomes zero and hence power generation from Rooikrans and the NPV becomes zero. The model outcomes for this condition are presented in Figure 12 and are in agreement with this extreme condition.

**Figure 12**  
Extreme conditions test of the RE-model

